(12) EUROPEAN PATENT SPECIFICATION

(54) **SINGLE POLARIZATION FIBER AND AMPLIFIER**

FASER UND VERSTÄRKER MIT EINER POLARISIERUNG

FIBRE ET AMPLIFICATEUR A POLARISATION UNIQUE

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(56) References cited:
EP-A- 0 486 930   US-A- 4 666 235

• OPTICAL FIBER COMMUNICATION
CONFERENCE. (OFC), SAN FRANCISCO, JAN.
22 - 26, 1990, vol. 1, 22 January 1990, INSTITUTE
OF ELECTRICAL AND ELECTRONICS
ENGINEERS, page 24 XP000146226 MELTZ G ET
AL: "IN-FIBER BRAGG GRATING TAP" cited in
the application
• OPTICS LETTERS, vol. 19, no. 24, 15 December
1994, pages 2101-2103, XP000485804
KRINGLEBOTN J T ET AL:
"ER3+:YB3+-CODOPED FIBER
DISTRIBUTED-FEEDBACK LASER"

EP 0 758 493 B1

Description

Cross References to Related Applications

[0001] Copending US Patent Application, Serial No. 08/398,206, entitled, "Polarized Fiber Laser Source", filed contemporaneously herewith, contains subject matter related to that disclosed herein.

Technical Fi ld

[0002] This invention relates to single polarization optical components and more particularly to single polarization fibers and amplifiers.

Background Art

[0003] It is known in the art of fiber optics that a polarization preserving (or maintaining) fiber will maintain the polarization of light launched into one end such that the light exiting from an opposite end has substantially the same polarization as that which entered it. However, if an elliptically polarized or circularly polarized light enters a polarization maintaining fiber, the light that exits the fiber will be polarized along both orthogonal polarization modes corresponding to the input signal.

[0004] However, it would be desirable to obtain an optical fiber which receives randomly elliptically polarized input light and provides output light polarized only along a single polarization.

[0005] It is also known that a fiber optic amplifier may be made using polarization preserving fiber. However, such an amplifier has the same drawbacks as the aforementioned optical fiber when a randomly elliptically polarized input signal is incident thereon and the desired output signal is a singularly polarized signal.

[0006] Thus, it would be desired to provide an optical amplifier which provides an output signal polarized only along a single polarization mode.

[0007] US-A-4 666 235 describes a fibre optic polarizer comprising a multilayer dielectric phase grating placed adjacent a half coupler that includes a fiber portion with reduced cladding thickness, such that light of a selected polarization remains in the fibre while light of another polarization is coupled out of the fibre.

Disclosure of Invention

[0008] Objects of the invention include provision of a single polarization optical fiber and/or amplifier which provides output light polarized substantially along a single polarization mode.

[0009] According to the present invention a single polarization device, comprises a non-polarization preserving solid optical waveguide which propagates light having polarization components along a first polarization mode and along a second polarization mode; a slanted grating tap formed within the waveguide and oriented at a predetermined angle with respect to the longitudinal axis of the waveguide, and having a predetermined grating spacing, grating length, and grating strength so as to couple-out of the waveguide a predetermined amount of the first polarization over a predetermined wavelength range and pass the second polarization as an output light from the waveguide, the output light being polarized substantially along the second polarization; and the grating length extending over substantially the entire length of the waveguide.

[0010] According further to the present invention, a portion of the waveguide is doped with a rare-earth dopant. According still further to the present invention, the rare-earth dopant comprises erbium.

[0011] The invention represents a significant improvement over the prior art by providing an optical fiber which only propagates a single polarization mode of light. In an alternative embodiment, all or a portion of the optical fiber may be doped with a rare-earth dopant to provide a polarization sensitive optical amplifier, thereby providing amplified optical output signal only along a single polarization mode.

[0012] The foregoing and other objects, features and advantages of the present invention will become more apparent in light of the following detailed description of exemplary embodiments thereof as illustrated in the accompanying drawings.

Brief Description of Drawings

[0013] Fig. 1 is a schematic block diagram of a single polarization optical fiber in accordance with the present invention.

[0014] Fig. 2 is a schematic block diagram of a single polarization optical amplifier in accordance with the present invention.

[0015] Fig. 3 is a schematic block diagram of a single polarization optical fiber and amplifier, in accordance with the present invention.

Best Mode for Carrying out the Invention

[0016] Referring to Fig. 1, a single polarization optical fiber comprises a predetermined length L of optical fiber 10, e.g., non polarization preserving optical fiber. The fiber has impressed therein a continuous slanted Bragg grating tap 12 having a predetermined angle θ with respect to a longitudinal axis of the fiber 10 and a predetermined spacing D between peaks in the periodic perturbation of the refractive index of the optical core of the fiber 10.

[0017] An optical source 14 provides an optical output signal 16 which enters the fiber 10. The input signal 16 has a signal wavelength (or wavelength band) λ_s and may be randomly elliptically polarized having polarization components along two orthogonal polarization axes (or states or modes) as indicated by a dot 18 and a line 20 corresponding to, e.g., the "S" and "P" polarizations,

respectively.

[0018] The spacing D of the grating 12 is set so as to reflect the wavelength λ_s (or wavelength band) of the input signal out of the fiber 10, as indicated by lines 22. Also, the angle θ of the grating 12 is set at the Brewster wavelength angle (discussed her inafter), such that only (or primarily) light of one polarization, e.g., dot or "S" polarization, is coupled out of the fiber, as indicated by dots 24. Accordingly, light 26 which passes through the slanted grating tap 12 and exits the fiber 10 has a pr f-erential polarization along the "P" polarization state, as indicated by a line 28.

[0019] The percentage of the light 16 along the dot (or "S") polarization axis to be coupled-out of the fiber by the grating tap 12 is determined by the following relationship:

$$P_1 = P_0 \exp(-\gamma_{s,p}{}^* l) \qquad \text{[Eq. 1]}$$

or in terms of dB:

$$10 \log(P_1/P_0) = 4.343(-\gamma_{s,p}{}^* l) \qquad \text{[Eq. 2]}$$

where P_1 is the power of the transmitted light (for a given polarization state) that passes through the grating tap, P_0 is the power of the incident light (for a given polarization state), $\gamma_{s,p}$ is the fraction of light for a given polarization state coupled-out of the fiber per unit length of fiber grating tap (i.e., the loss per unit length), and 1 is the longitudinal length of the fiber grating tap.

[0020] The value for $\gamma_{s,p}$ is a function of Δn (peak refractive index change of the grating), d (diameter of fiber core), NA (numerical aperture between core and cladding), and λ_0 (wavelength of the incident light). For an Accutether® fiber having a core diameter d of 4.902 mm, a numerical aperture NA of 0.196, a grating Δn of 5.84 x 10⁻³, and an average refractive index of 1.46 (giving a grating fractional index change or "strength" of Δn/n = 0.004 or 0.4%), the values for γ_s and γ_p are:

γ_s=0.225537 mm⁻¹ (for the tapped-out "S" polarization); and
γ_p=2.57669 x 10⁻³ mm⁻¹ (for the un-tapped "P" polarization).

[0021] These values of γ_s and γ_p may be determined by modeling the grating tap as an optical phased array, or may alternatively be derived from optical mode coupling theory, such as that described in the text: A. Snyder et al, "Optical Waveguide Theory", Publ. Chapman and Hall Ltd, ISBN 0,412,24250,8 (1983). Also, the value of the loss y is proportional to (Δn)² for both "S" and "P" polarizations.

[0022] Thus, to provide a high percentage of polarization rejection, e.g., about 99.9%, of the "S" polariza-

tion over the "P" polarization the length of the grating tap can be calculated as follows.

$$P_p = P_{0p} \exp(-\gamma_p{}^* l) \qquad \text{[Eq. 3]}$$

$$P_s = P_{0s} \exp(-\gamma_s{}^* l) \qquad \text{[Eq. 4]}$$

taking the ratio of P_p to P_s gives:

$$10 \log(P_p/P_s) = 4.343(\gamma_s - \gamma_p) l \qquad \text{[Eq. 5]}$$

and P_p/P_s= 1000 (i.e., 1/.001); thus l = 31.06 mm or 3.1 cm.

[0023] Therefore, the length l of the grating tap should be about 3.1 cm for a grating having a Δn/n of 0.4% (which is typically considered a "strong" grating). Other grating lengths l and fractional index changes Δn/n may be used if desired. As indicated in Eq. 1, the longer the grating length l, the more light that is tapped out of the fiber. Also, the "stronger" the grating (i.e., the larger the fractional index change Δn/n), the more light that is tapped out. Further, as discussed hereinbefore, the fractional loss γ is proportional to the square of the refractive index change (Δn)² for the grating. Thus, for short fibers, a strong grating may be needed to provide the desired polarization rejection.

[0024] Regarding polarization sensitivity and the angle θ of the grating tap 12, it is known that a short slanted grating tap exhibits polarization sensitive reflection as is discussed in the article: G. Meltz et al, "In-fiber Bragg Grating Tap", Optical Fiber Communication Conference, 1990 Technical Digest Series, Vol. 1 (Jan. 1990). In that article, a short (5 mm) grating tap was formed in a polarization maintaining fiber to illustrate this principle. It is also known that the sensitivity of the slanted grating tap 12 to the polarization of incident light is related to the optical theory on Brewster's angle.

[0025] In particular, the grating 12 reflects light polarized normal to the plane of incidence (or parallel to the reflecting surface of the tap, or "S" polarized in Fig. 1), independent of the angle of incidence. However, light polarized parallel to the plane of incidence (or normal to the reflecting surface, or "P" polarized in Fig. 1) and incident on the grating at the Brewster's angle, is transmitted with minimal reflection. Thus, the angle of the grating tap 12 should be set such that the light incident on the grating tap is incident on the tap at the Brewster's angle. The Brewster's angle for a small fractional refractive index change (Δn/n) at the reflection interface, e.g., 0.05-0.1% (which is typical for a Bragg grating), is approximately 45 degrees; however, even for "strong" gratings (e.g., Δn/n=0.5%+) the angle is close to 45 degrees. More specifically, the known relationship for the Brewster's angle is:

$$\text{Tan } \theta_p = n_t/n_i \qquad \text{[Eq. 6]}$$

where θ_p is the angle of incidence of the light incident on the tap, n_t is the refractive index of the grating tap, and n_i is the incident refractive index outside the grating tap. Thus, the grating tap 12 will typically be set at about 45 degrees from the longitudinal axis of the fiber so as to allow the tap to reflect only light polariz d parallel to the reflecting surface of the grating tap. The angle θ of the grating tap 12 is related to the Brewster's angle by the relation: θ + θp =90 degrees. Thus, the angle of the grating tap can be readily determined from the Brewster's angle. The angle of the tap (from Eq.1) is based on the Δn for the grating used.

[0026]   Referring now to Fig. 2, a single polarization optical amplifier includes an optical fiber amplifier 50 having the slanted grating 12 impressed in the core thereof similar to that discussed hereinbefore with Fig. 1. The grating 12 has the predetermined angle θ with respect to the longitudinal axis of the fiber 50 and the predetermined spacing D between peaks in the periodic perturbation of the refractive index of the optical core. The fiber 50 is doped with a rare earth dopant, e.g., erbium, which acts as an optical gain or amplifying medium. All or a portion of the fiber 50 may be doped if desired.

[0027]   The signal 62 passes through an optional optical isolator 63 which allows light to pass in only one direction(discussed more hereinafter). The light 62 then enters the optical fiber 50.

[0028]   A pump and signal source 60 provides an output signal 62 having a pump wavelength λ_p and an input signal wavelength λ_s. Alternatively, the source 60 may comprise a separate pump source (not shown) which provides an optical signal λ_p and a separate input signal source (not shown) which provides an input optical signal having a wavelength λ_s, and both signals being coupled together to form the light 62.

[0029]   The light 62 may be randomly elliptically polarized which can be decomposed along the two orthogonal polarizations as indicated by the dot 18 and the line 20, similar to that discussed hereinbefore with Fig. 1.

[0030]   The angle θ, the spacing D, the fractional index change (or strength; Δn/n), and the length of the grating tap 12 are set to reflect (or couple-out) a predetermined amount of one polarization, and a predetermined wavelength (or wavelength band), of the light 62 out of the fiber 50 amplifier, as indicated by lines 64, in a similar manner to that discussed hereinbefore with Fig. 1. The polarization of light which is coupled-out of the fiber amplifier 50 is indicated by dots 66.

[0031]   As is known, in an optical amplifier, the pump wavelength λ_p excites the rare-earth gain medium within the fiber 50 to an energy state which will cause the gain to exhibit stimulated emissions of photons at a predetermined wavelength or wavelength band. The rare-

earth dopant should be designed so as to provide emissions having the same wavelength (or wavelength band) as the input signal λ_s, thereby providing optical amplification of the input signal portion of the signal 62 through optical amplifier by stimulated emissions from the gain medium which was excited by the pump wavelength λ_p. The amount of amplification that occurs, as is known, will be related to th length of the gain medium, the power of the pump, and the type of gain medium used. The amplifier can also be viewed as a broad-band super-fluorescent (or super-luminescent) source if only a pump signal and no input signal (to be amplified) is provided.

[0032]   Because the grating tap 12 reflects one polarization, the other polarization passes through the grating tap 12 and travels along the doped fiber, stimulating more emissions along the length of the fiber amplifier 50 and ultimately exits the fiber 50 as indicated by a line 68, having one polarization, as indicted by a line 70, at the wavelength λ_s. There may also be some residual pump energy at the wavelength λ_p in the output light 68 if the gain medium of the fiber 50 does not completely absorb the pump wavelength radiation.

[0033]   Thus, as discussed hereinbefore with Fig. 1, the slanted grating 12 reflects or couples out a predetermined portion of the light at the signal wavelength along a predetermined polarization. Accordingly, the amplifier of Fig. 2 provides a substantially single polarization output signal 68 when the input signal 62 is randomly elliptically polarized, depending on the length l and strength (Δn/n) of the grating tap, as discussed hereinbefore.

[0034]   The optical amplifier 50, as is known, emits light from both ends of the amplifier 50 as indicated by the line 68 and a line 72. As such, the isolator 63 prevents the amplified light 72 from entering and disrupting the operation of the pump and/or signal source 60. However, the isolator is not required if the source 60 has adequate isolation from external light.

[0035]   Also, it should be understood that the amplifier 50 may be pumped from both ends of the fiber instead of only one end, as indicated by a dashed line 74. In that case, light will also be tapped out of the fiber as indicated by dashed lines 76 having a polarization indicated by dots 78. Also, in that case, the output amplified light may be extracted by a coupler or beam splitter (not shown). Also, it should be understood that instead of tapping out the dot ("S") polarization and passing the line ("P") polarization, the invention may instead tap out the line ("P") polarization and pass the dot ("S") polarization.

[0036]   Additionally, because an optical amplifier may be used to amplify broadband light, and because the grating tap 12 may be designed with a grating spacing D so as to couple out a broad wavelength band, the amplifier of the present invention may also be used as a broad-band polarization sensitive amplifier. In particular, as is known, the grating spacing D is related to the reflection wavelength of a Bragg grating. More specifi-

cally, the larger the spacing the broader the wavelength reflectivity profile. Thus, by increasing the grating spacing D the polarization sensitive wavelength band of the amplifier is increased. However, if only a pump input signal is provided, the output light will be solely generated by emissions from the gain medium, and an broadband incoherent super-fluorescent (or super-luminescent) source is provided.

[0037] Referring to Fig. 3, in a single polarization fiber and amplifier embodiment of the present invention, the grating tap 12 extends a predetermined length l along an optical fiber 100, similar to the fiber 10 (Fig. 1) and provides polarization sensitive light propagation, as discussed hereinbefore with Fig. 1. A region 102 of the fiber 100 is doped with a rare-earth dopant, e.g., erbium, similar to the doped fiber 50 (Fig. 2), which provides polarization sensitive light amplification of the input wavelength λs when excited or pumped by a pump wavelength λp, as discussed hereinbefore with Fig. 2. A portion of the input light 62 along the "S" or dot polarization over a predetermined wavelength band is tapped out of the fiber 100, as indicated by line 110. The light which is passed by the grating (and amplified by the gain, if used), is indicated by a line 112, having substantially a single a polarization 114. Symmetrically, if the input light 74 enters the fiber 100 from the right side a portion of the light 74 along the "S" or dot polarization over a predetermined wavelength band is tapped out of the fiber 100, as indicated by lines 116. The light which is passed by the grating 12 (and amplified by the gain 102, if used), is indicated by a line 116, having substantially a single a polarization 120.

[0038] The fiber 100 may have two regions 106,108 at either end of the fiber which does not have the grating 12 impressed therein. The maximum allowable length of fiber regions 106,108 without the grating tap 12 depends on the amount of birefringence in the fiber and the magnitude of environmental perturbations, e.g., bending, twisting, crimping, etc., along the fiber portion without the grating tap, which cause polarization coupling in a fiber, as is known in the art. For best performance, and in accordance with the present invention, the grating tap 12 extends along substantially the entire length of the fiber to ensure single polarization performance of the fiber and/or amplifier. There may be gaps along the grating tap 12 similar to the regions 106,108 which propagate light over a predetermined length but do not alter the polarization.

[0039] Alternatively, the embodiment of Fig. 3 need not have a gain region. In that case, the fiber 100 with the tap 12 would be solely a single polarization fiber without amplification. Further, alternatively, in the embodiment of Fig. 3 the gain region 102 may extend over the entire length l of the grating 12.

[0040] Furthermore, the invention does not require the use of polarization preserving (or maintaining) fiber because the grating 12 either extends over the entire length of the fibers 10,50 (as shown in Figs. 1 and 2,

respectively), or extends for at least a sufficient length substantially along the entire length of the fiber so as to provide a predetermined amount of polarization rejection and the remaining fiber being short enough so as not to allow polarization crossover, crosstalk, or coupling between polarizations (as shown in Fig. 3).

[0041] It should be understood that the invention will work equally well with any solid optical waveguide, e.g., a planar rib or chann l optical waveguide instead of an optical fiber.

[0042] Also, the fibers 10,50 may be made of a fiber having more than one spatial mode (i.e., a multi-spatial mode fiber). In that case, the polarization of light propagating along each mode may be coupled out of the fiber by one or more slanted grating taps (depending on the magnitude of the difference between the optical frequency associated with each spatial mode and the bandwidth of the grating tap), in a manner similar to that described in U.S. Patent No. 5,048,193, entitled "Optical Waveguide Embedded Transverse Spatial Mode Discrimination Filter", to Meltz et al.

Claims

1. A single polarization device, comprising:

   a non-polarization preserving solid optical waveguide (10;50;100) which propagates light (16;62;74) having polarization components along a first polarization mode (18) and along a second polarization mode (20);
   a slanted grating tap (12) formed within said waveguide and oriented at a predetermined angle (θ) with respect to the longitudinal axis of said waveguide, and having a predetermined grating spacing (D), grating length (l), and grating strength so as to couple-out of said waveguide a predetermined amount (22;64; 110) of said first polarization over a predetermined wavelength range and pass said second polarization (28;70;114;120) as an output light (26;68;112;118) from said waveguide, said output light being polarized substantially along said second polarization; and
   said grating length extending over substantially the entire length (L) of said waveguide.

2. The single polarization device of claim 1 wherein a portion (102) of said waveguide comprises a gain medium.

3. The single polarization device of claim 2 wherein said gain medium comprises a rare-earth dopant.

4. The single polarization device of claim 1 wherein said waveguide comprises an optical fiber.

5. The single polarization device of claim 1 further comprising a pump signal within said waveguide which excites said gain medium, said gain medium emitting said light in said waveguide.

6. The single polarization device of claim 5 wherein said light emitted from said gain medium is broadband light.

Patentansprüche

1. Einzelpolarisationsbauelement, umfassend:

einen nicht-polarisationserhaltenden optischen Festkörper-Wellenleiter (10; 50; 100), der Licht (16; 62; 74) mit Polarisationskomponenten entlang einem ersten Polarisationsmodus (18) und entlang einem zweiten Polarisationsmodus (20) ausbreitet;

einen Schräggitterabgriff (12), der in dem Wellenleiter ausgebildet ist und unter einem vorbestimmten Winkel (θ) bezüglich der Längsachse des Wellenleiters orientiert ist, und der außerdem einen vorbestimmten Gitterabstand (D), eine vorbestimmte Gitterlänge (l) und Gitterstärke aufweist, um aus dem Wellenleiter eine vorbestimmte Menge (22; 64; 110) der ersten Polarisation über einem vorgegebenen Wellenlängenbereich auszukoppeln und die zweite Polarisation (28; 70; 114; 120) als Ausgangslicht (26; 68; 112; 118) aus dem Wellenleiter auszugeben, wobei das Ausgangslicht im wesentlichen entlang der zweiten Polarisation polarisiert ist; und

wobei die Gitterlänge sich über im wesentlichen die Gesamtlänge (L) des Wellenleiters erstreckt.

2. Einzelpolarisationsbauelement nach Anspruch 1, bei dem ein Abschnitt (102) des Wellenleiters ein Verstärkungsmedium aufweist.

3. Einzelpolarisationsbauelement nach Anspruch 2, bei dem das Verstärkungsmedium einen Seltenerd-Dotierstoff aufweist.

4. Einzelpolarisationsbauelement nach Anspruch 1, bei dem der Wellenleiter eine optische Faser aufweist.

5. Einzelpolarisationsbauelement nach Anspruch 1, weiterhin umfassend ein Pumpsignal innerhalb des Wellenleiters, welches das Verstärkungsmedium anregt, wobei das Verstärkungsmedium das Licht in dem Wellenleiter emittiert.

6. Einzelpolarisationsbauelement nach Anspruch 5, bei dem das von dem Verstärkungsmedium emittierte Licht breitbandiges Licht ist.

Revendications

1. Dispositif à polarisation simple, comportant :

un guide d'ondes optique à solide (10 ; 50 ; 100), ne préservant pas la polarisation, qui permet à une lumière (16 ; 62 ; 74), qui possède des composantes de polarisation, de se propager suivant un premier mode de polarisation (18) et suivant un second mode de polarisation (20) ;

une prise à réseau incliné (12) formée à l'intérieur dudit guide d'ondes et orientée suivant un angle prédéterminé (o) par rapport à l'axe longitudinal dudit guide d'ondes, et ayant un pas de réseau (D), une longueur de réseau (ℓ) et une force de réseau prédéterminés de manière à transmettre hors dudit guide d'ondes une quantité prédéterminée (22 ; 64 ; 110) de ladite première polarisation sur une plage de longueurs d'onde prédéterminée et à laisser passer ladite seconde polarisation (28 ; 70 ; 114 ; 120) comme lumière de sortie (26 ; 68 ; 112 ; 118) à partir dudit guide d'ondes, ladite lumière de sortie étant polarisée essentiellement suivant ladite seconde polarisation ; et

ladite longueur du réseau correspondant pratiquement à toute la longueur (L) dudit guide d'ondes.

2. Dispositif à polarisation simple selon la revendication 1, dans lequel une partie (102) dudit guide d'ondes est constituée d'un milieu actif.

3. Dispositif à polarisation simple selon la revendication 2, dans lequel ledit milieu actif est constitué d'une terre rare dopante.

4. Dispositif à polarisation simple selon la revendication 1, dans lequel ledit guide d'ondes est constitué d'une fibre optique.

5. Dispositif à polarisation simple selon la revendication 1, comprenant en outre un signal de pompage au sein dudit guide d'ondes qui excite ledit milieu actif, ledit milieu actif émettant ladite lumière dans ledit guide d'ondes.

6. Dispositif à polarisation simple selon la revendication 5, dans lequel ladite lumière émise par ledit milieu actif est une lumière large-bande.
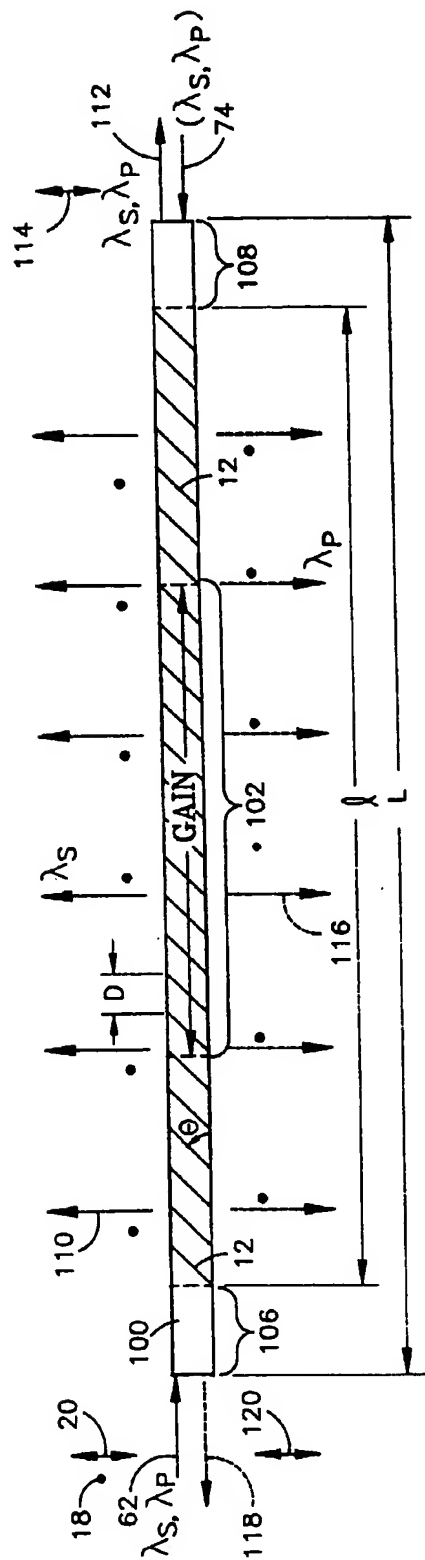
fig. 1

fig. 2

fig.3